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13. ABSTRACT (Maximum 200 words)

The physics of buried mine detection in offshore sediments and in the surf zone was investigated. Optical techniques are useless because they cannot penetrate sediments while magnetic techniques are of low value because of low resolution, short range, and the introduction of non-magnetic mines. For buried mine detection in the off-shore sediment, acoustic penetration at shallow grazing angles was explored. An experiment was conducted jointly with SACLANTCEN to measure sound propagation into a sediment in the 500 Hz to 2 kHz band, and a theoretical fast field model was developed to model the penetration. In the surf zone, where bubble clouds are expected to render acoustic methods unreliable, seismic sonar methods were explored as a means to echo range off buried targets. Tests with controlled pulses revealed that the far-field response was dominated by two interface waves. The results have been very encouraging.

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Physics of Buried Mine Detection and Classification

Final Technical Report under

Grant: N00014-94-1-0485

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1 March 1994 - 28 February 1995

Long-term goals:

A better understanding of the science and engineering of buried mine detection in (1) offshore and (2) surf zone sediments, leading to safe, standoff detection technologies. This project is part of a leveraged investment program for Office of Naval Research (ONR) and Advanced Research Projects Agency (ARPA) offices, which involves SPECWAR and U.S. Marine Corps (USMC) interests, to pursue major research thrusts already begun by the authors, that will lead the way to systems development. The work is further leveraged by the cooperation of the SACLANT Undersea Research Centre (SACLANTCEN), which will provide cooperating seafloor scientists, research tools and research vessels in a joint effort to research the basic Physics of the governing processes.

Scientific or technological (S&T) objectives:

(1) Theoretical understanding and modeling of the Biot slow wave and the leakage wave for exploitation in the detection and classification of buried targets.

(2) A seismic interface wave sonar concept, for the detection and classification of buried and proud mines in the surf zone.

Background:

The detection of buried mines remains an unsolved problem in offshore sediments and in the surf zone. Optical techniques are useless because they cannot penetrate sediments while magnetic techniques are of low value because of low resolution, short range, and the introduction of non-magnetic mines. (1) With respect to buried mines in the off-shore sediment, it is desired to have long range systems, operating at low grazing angles for maximum standoff distance. On the basis of viscoelastic theory, it has long been thought that there is a critical grazing angle that precludes penetration at low grazing angles into most unconsolidated sediments. However, this conclusion has been shown to be erroneous. (2) In the surf zone, extensive clouds of micro bubbles generated by collapsing wave processes scatter and attenuate acoustic frequencies

capable of penetrating the sediments. Avoiding the opacity of bubble zone scattering may require seismic sonar methods, in which Sholte waves are generated in the sediment and used to echo range off buried targets.

Approach:

(1) Mines buried in offshore sediments. Due to the availability of scientific knowledge, theory, models, and research tools developed at ARL:UT in prior year efforts sponsored by NRL and ONR, we were able to initiate research at the forefront of the field, without the normal start up time required to "come up to speed". The emphasis was on sand since it supports all three types of waves, the Biot fast, slow and shear waves. The ARL:UT Biot model[1] of acoustic penetration has been found to agree with in-situ data in the 10 to 100 kHz band. The objective for FY94 was to verify and extend the range of the ARL:UT Biot model into the 1 to 10 kHz band. There were strong trend changes in this band that severely tested the validity of the model.

(2) Mines buried in the surf zone. The Sholte wave is a seismo-acoustic interface wave that travels very slowly in unconsolidated sediments. Since these waves are highly attenuated, low frequency operation is required. Due to the conduct of prior years efforts in ASW seismo-acoustics at SACLANTCEN and at ARL:UT (sponsored by ARPA MSTO), considerable experience, research tools, testbed sites, and computational models were brought to bear on the development of the seismic interface wave sonar concept described above, without much need for "start up time development". Although a new target strength theory was needed for this specialized problem, it was facilitated by previous theoretical developments at the participating organizations. Similar considerations apply to the new experiments that were done to develop the concept.

Accomplishments and results:

(1) Offshore buried mine problem. There are two main accomplishments, (a) an experiment was conducted jointly with SACLANTCEN to measure sound propagation into a sediment in the 500 Hz to 2 kHz band, and (b) modifications in the OASES 1.6 fast field model to allow the modeling of porous sediment layers were ported to OASES 1.7.

A joint experiment was conducted by SACLANTCEN in cooperation with ARL:UT to measure sound propagation into a sandy sediment. A hydrophone array was planted in a sandy sediment, at a water depth of 10 m, in the Gulf of the Poets, Lerici, Italy, from the SACLANTCEN research boat, R/V Manning. The configuration of the buried array is shown in Fig. 1. A sparker was towed by

the Manning and used to transmit sound waves towards the hydrophone array. The signal from a sparker typically contains two pulses, the first corresponding to the initial expansion of the gas bubble generated by the spark and the second from the bubble collapse. Part of the source track is shown in Fig. 2, in particular the source positions at pings 41 to 44 and 54 to 57. The signal from each group of 4 pings was coherently summed to synthesize a 4-element transmitting array. The signals were analyzed for sediment acoustic wave direction and speed. In all cases, the first arrival is the evanescent wave traveling horizontally due to the bubble expansion pulse, followed 6 ms later by the second due to the bubble collapse. In between these two pulses, a slower wave is detectable. The results for pings 41 to 44 is shown in Fig. 3; Fig. 3(a) shows the signals from hydrophones 1 through 4, and Fig. 3(b) shows the analysis results from 3 time slices. The first and third time slices correspond to the first arrival of the two pulses, in the form of evanescent waves at a speed of approximately 1500 m/s, and traveling horizontally. A slower wave is discernible between the two pulses, heading downward at an angle of approximately 45° at a speed of 1 km/s, as shown in the analysis result for the second time slice, in Fig. 3(b); the speed and direction is consistent with a Biot slow wave in sand. In the case of pings 54 to 57, there is also some acoustic energy between the two evanescent pulses, as shown in Fig. 4(a), but its speed and direction is imprecise, as shown in the analysis result of the second time slice, in Fig. 4(b). The main differences between pings 41 - 44, and 54 - 57, is that the first group arrives from the west, and the second from the south east. This suggests that the sediment is either inhomogeneous, or anisotropic in its response, or both.

Although the site was nominally a sandy site according to previous survey data from 1986, a grab sample brought up by the divers contained more than 75% silt. This conflicting information and the anisotropic acoustic results supports the hypothesis that the site is not uniform. Perhaps there are patches of sand and silt.

The measured sediment acoustic wave functions were also compared to model predictions, using OASES1.7-B, a fast field model obtained by modifying OASES1.7[2] to include porous layers. This model assumes a horizontally stratified medium, and cannot handle non-uniform layers. Comparisons were made with predictions for a muddy sediment modeled after the grab sample, and a sandy one based on the 1986 core samples. The results are shown in Fig. 5. The measured acoustic signal, from ping 44, appears to be in better agreement with the mud model based on the grab sample taken on site, as far as the evanescent waves are concerned. Neither model contains any features

that properly match the slow wave detected in pings 41 to 44. Clearly, the sediment properties are considerably more complicated than the models.

In summary, we have conducted a joint experiment with SACLANTCEN, and succeeded in detecting a Biot slow wave in the 500 Hz to 2 kHz band, penetrating the sediment to depth of at least 3 m. Initial experimental results were presented at the 128th meeting of Acoustical Society of America[3]. We also succeeded in constructing a fast field layered medium propagation model for elastic and poro-elastic sediments, by modifying OASES1.7 from Schmidt, MIT. Comparisons with the theoretical model will be presented at the 129th meeting of Acoustical Society of America[4]. The new model will be available via INTERNET through an ftp account. The model was able to match the gross features of the measured acoustic signals from the sediment penetration experiment, but significant differences remain to be resolved in the follow on project.

(2) Surfzone buried mine problem. Accomplishments on this task were made in areas of both theory and experiment: For theory, a method was derived to compute and efficiently estimate seismo-acoustic interface wave scattering (SIWS) strengths, based on properties of an object and the medium in which it is buried. To test the validity of this theory, as well as the concept overall, a field experiment was carried out on a natural hard-sand beach near Corpus Christi, Texas.

The perturbative scattering theory developed to model the SIWS represents an attempt to balance efficiency with generality. Computing the wave scattered from a complicated buried object is analytically unfeasible, and numerically costly. However, in many situations of interest, a buried object can be approximated as one or a few pointlike discontinuities in a layered background medium. Further, if interface waves are the excitations of interest, remote layers can often be ignored when estimating reflection properties. Therefore, the approach taken was to solve the homogeneous wave equation for two half-spaces, one fluid and the other a linear elastic solid, with a pointlike discontinuity located in the solid near the interface. This is done within the framework of perturbation theory, giving an answer which may be made as simple or as refined as the situation demands. The complete calculation will be presented at the 129th meeting of the Acoustical Society of America[5], and a sample result of interest for this application noted here.

When a plane interface wave is sent toward a compact buried object, the reflection takes the form of outgoing cylindrical interface waves, as well as scattering into the volume, which is rapidly lost with range. The angular

dependence of such a wave can be expanded in monopole, dipole, quadrupole and higher moments, yielding a coefficient for each. How strongly an object scatters is determined by how large a discontinuity it represents in density, compressibility and shear stiffness from the medium around it. When these parameters are represented in dimensionless form, the scattering calculation produces a simple matrix of numbers, whose components tell how much amplitude in each moment is due to each material discontinuity. A sample matrix, computed for typical sand properties, is shown in Fig. 6. (The superscript indicates that this is the result of first-order perturbation theory.) The columns denote, respectively, amplitudes for monopole, dipole and quadrupole scattering, and the rows give the contributions from compressibility, density and shear discontinuities. So, for example, if the buried object causes a 100% (factor of 1) discontinuity in density over roughly a cubic wavelength (but no other mismatch), it will produce a scattered monopole wave that is 0.1795 as large as the incident plane wave (at the scatterer), a dipole wave 0.0004 as large, and no quadrupole. From this expression it is clear that most interface wave scattering will generally be monopole in nature, driven by discontinuties in density. The ability to simply compute such matrices with this theory makes the analysis of scenarios, as well as estimation of sonar performance, an efficient process.

The predictions of this theory were tested in actual field conditions, in an experiment with a suite of targets, which were insonified to produce echoes. The experiment was carried out on a natural hard-sand beach of the Gulf of Mexico near Corpus Christi, Texas. It revealed a number of interesting features of the SIWS concept.

First, a natural sand beach was an excellent laboratory for testing propagation and scattering of seismo-acoustic interface waves. Analysis of the dispersion curves of interface waves created by an impulse source (mechanical thumper), at ranges of one to several hundred meters, revealed that significant dispersion or layering structures occurred at depths greater than the wavelengths used to search for objects. Thus the beach provided a simple, nearly non-dispersive medium for all subsequent tests.

Tests with controlled pulses from a primitive seismo-acoustic transducer (a modified NRL J-11) then revealed that the interface response in the far field was dominated by the classic two interface waves of Scholte and Strick[6]. Two cleanly separated arrivals were visible, with velocities of 115 m/s and 90 m/s, respectively. The faster wave was dominantly horizontal and prograde, and the slower wave was dominantly vertical and retrograde. Because of the linear

motion of the source used, both waves were created, and in general both occurred as reflections from insonified targets, in subsequent tests.

A technique of polarization filtering in the time domain was used to extract RMS amplitudes of incident and reflected signals, to separate them according to the kind of interface mode being received, and to isolate them above backgrounds. An application with a target present is shown in Fig. 7. The target used was a Titanium cylinder with mass 37.9 kg. In the first case, the receiver was placed between the source and target, and the longitudinal horizontal geophone was sampled, to look for backscatter. In the second case, the receiver was placed transverse to the source-target line, and the transverse geophone used, to look for side-scatter. In both cases the source-target range was 10 m and the target-receiver range was 3 m.

As expected, the direct blast is much larger than the reflection from this relatively low-density target, and is visible primarily in the longitudinal and vertical geophones, as shown in the leftmost frames of Fig. 7. The reflected signal predicted by the matrix in Fig. 2 for these experimental conditions is between 2% and 12% of the signal incident on the target. This order of magnitude is in excellent agreement with the data, and the feature and wave identifications shown in the figure are consistent in both polarization and travel time to better than the width of the pulse envelope.

Impact on S&T, or transition/integration expected:

(1) Offshore problem. Previous attempts at buried minehunting sonar development were less than optimum because of a lack of understanding of acoustic interactions with the ocean sediment. The final result from this project will contribute to the theoretical modeling in support of a new buried mine sonar design. The improved understanding of bottom penetrating acoustics also impacts bottom reverberation modeling and sonar performance models, and will lead to upgrades of models, such as CASTAR, SPM, SEARAY and MINERAY, in the near future.

(2) Surfzone problem. More sonar concepts and configurations can be considered than it was possible to test effectively with first-generation equipment. Even with limited resources, the current experiments provided compelling evidence of their feasibility, and refinements in technique based on what has been discovered will make it possible to test them quantitatively in future implementations.

The work initiated under this ONR grant in FY94 is already beginning to transition to funding for engineering demonstrations at ARPA, Marine Systems

Technology Office (MSTO), in the funding of a FY95 Task Description, which includes preliminary 6.2 tasking on this problem.

Relationship to other projects:

(1) Offshore problem. This project has directly benefited from results of previous projects, particularly the NRL high frequency acoustics program and ONR sponsored research projects into Biot's theory.

(2) Surfzone problem. This project is related to and has benefited from seismo acoustic R&D on ASW in shallow water, funded by ARPA MSTO at ARL:UT, under SPAWAR Contract N000-94-1-0082. It is also related to and mutually benefits seismo acoustic research conducted by NATO at the SACLANT Undersea Research Centre, La Spezia, Italy.

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3. Nicholas P. Chotiros, Morris Stern, Adrienne Mautner, Åge Kristensen, and Enzo Michelozzi, "Comparison of theory and experiment of acoustic bottom penetration in a shallow water site", J. Acoust. Soc. Am. accepted for presentation at 129th meeting, May 1995.
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6. Scholte, J., On true and pseudo Rayleigh waves, *Proc. Kon. Ned. Akad. v. Wetensch.*, **52**, 652-653, 1949 and Strick, E., Propagation of elastic wave motion from an impulsive source along a fluid/solid interface: Part III. The pseudo-Rayleigh wave, *Philos. Trans. Roy. Soc. Lond.*, **A 251**, 488-523, 1959.

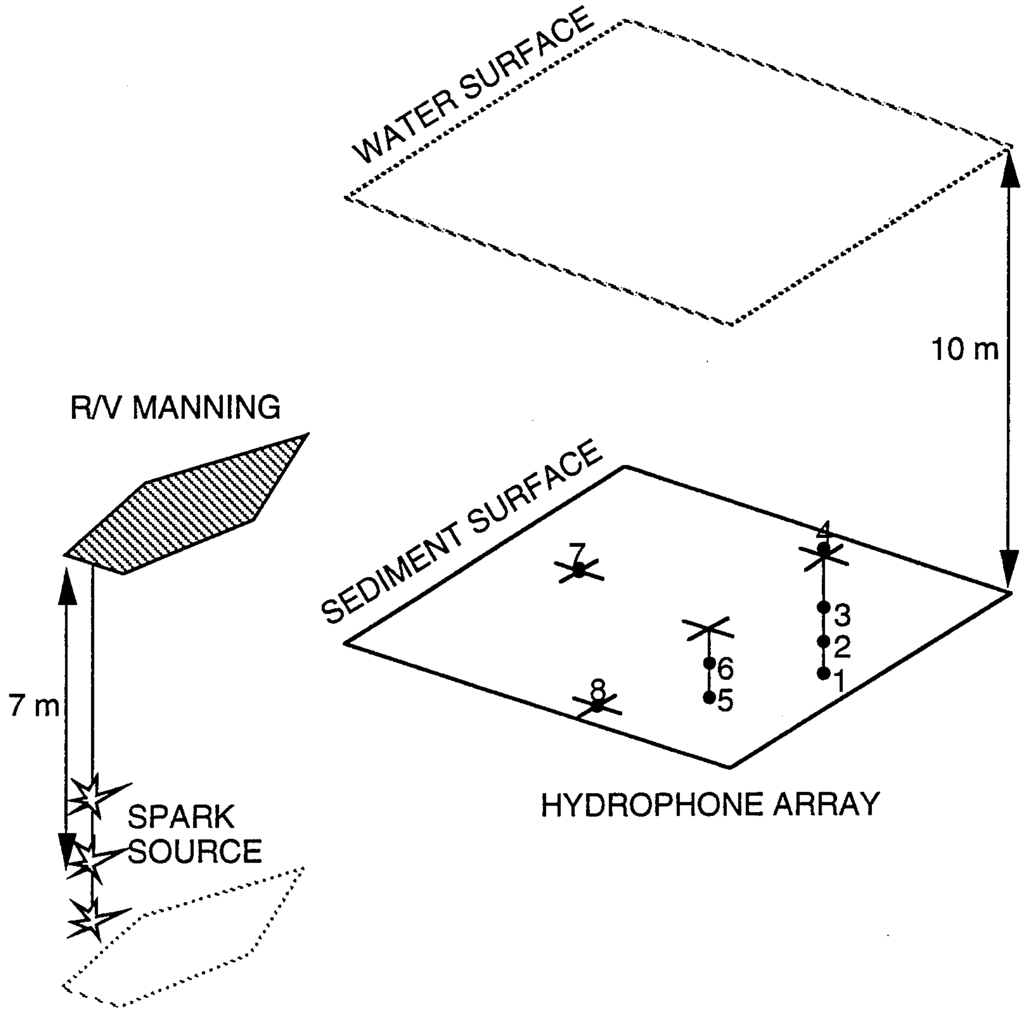

Figure 1.
Buried hydropohone array and spark source

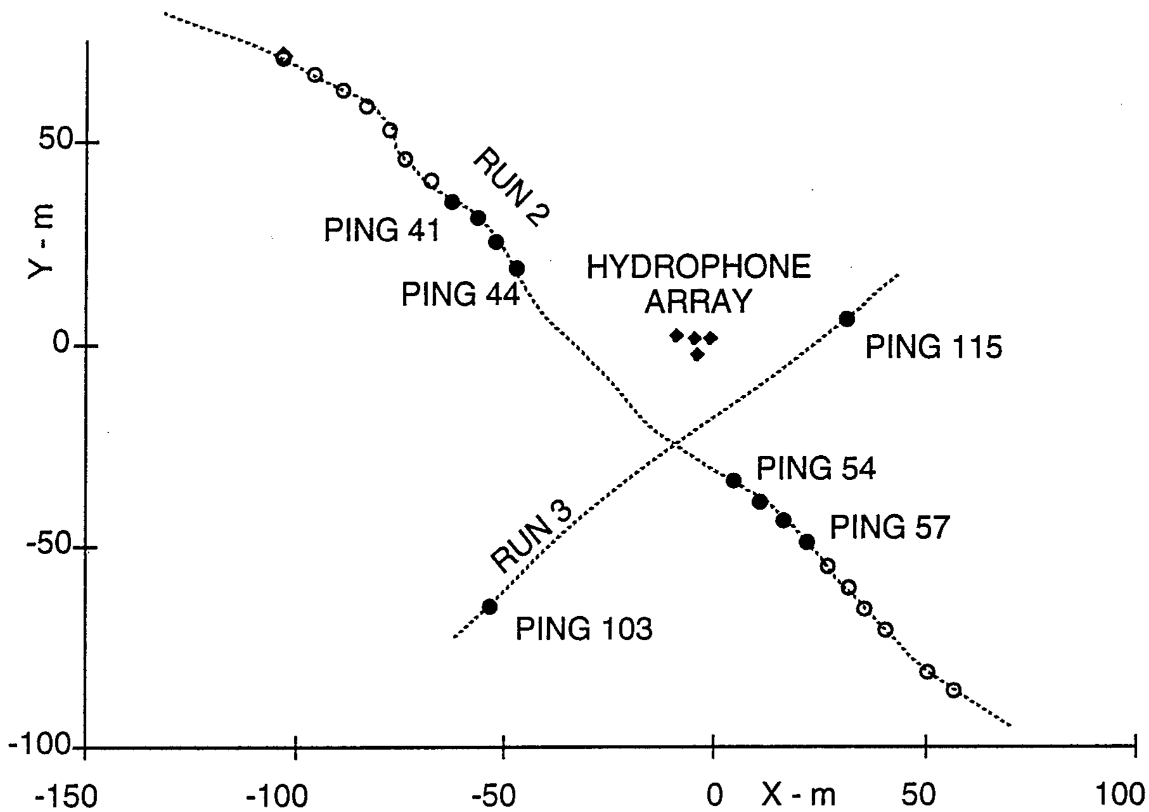

Figure 2.
Source positions on runs 2 and 3

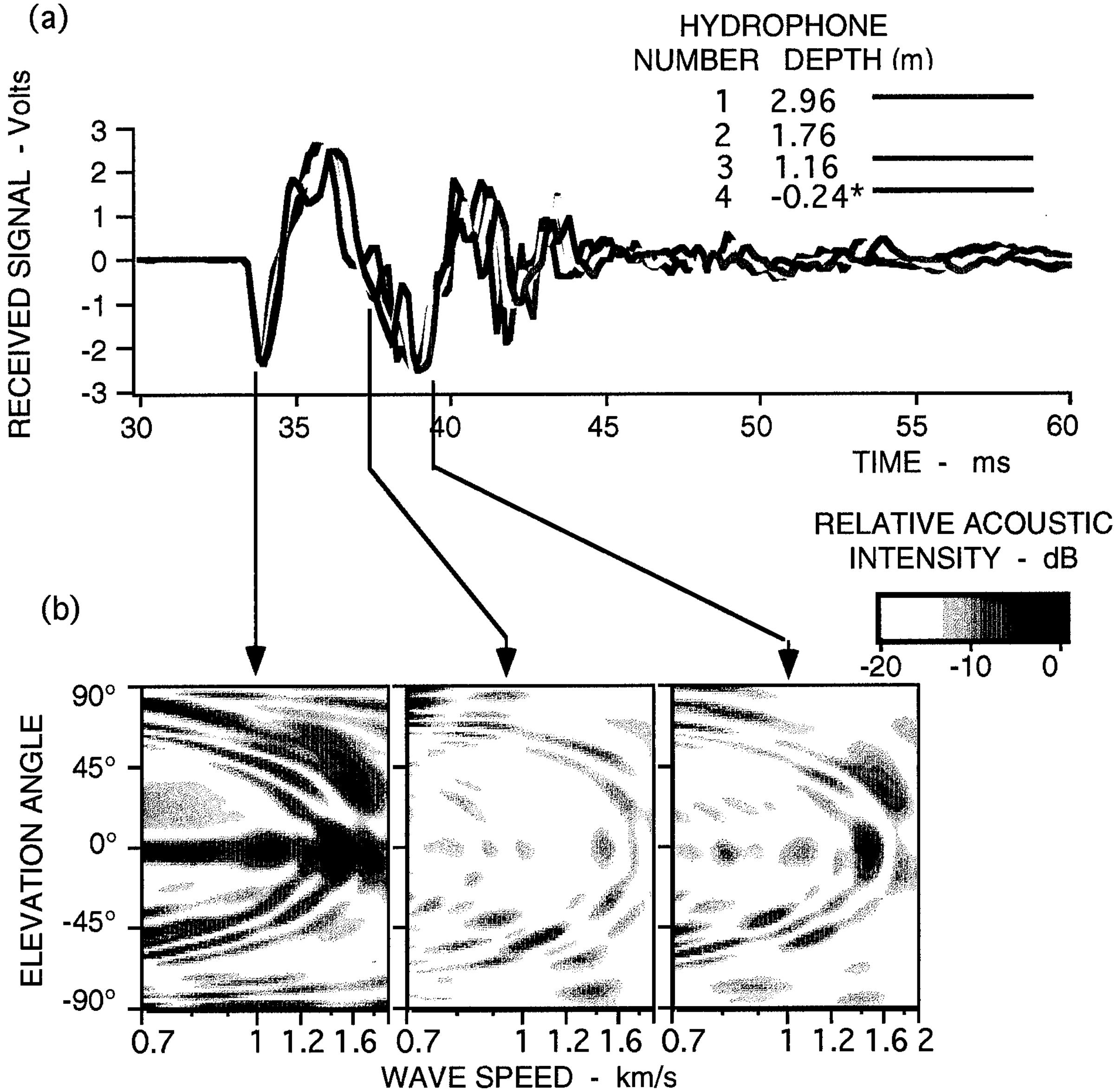

Figure 3.
Pings 41 to 44
(a) Signals received at hydrophones 1 - 4 at ping 44
(b) Direction and speed analysis results

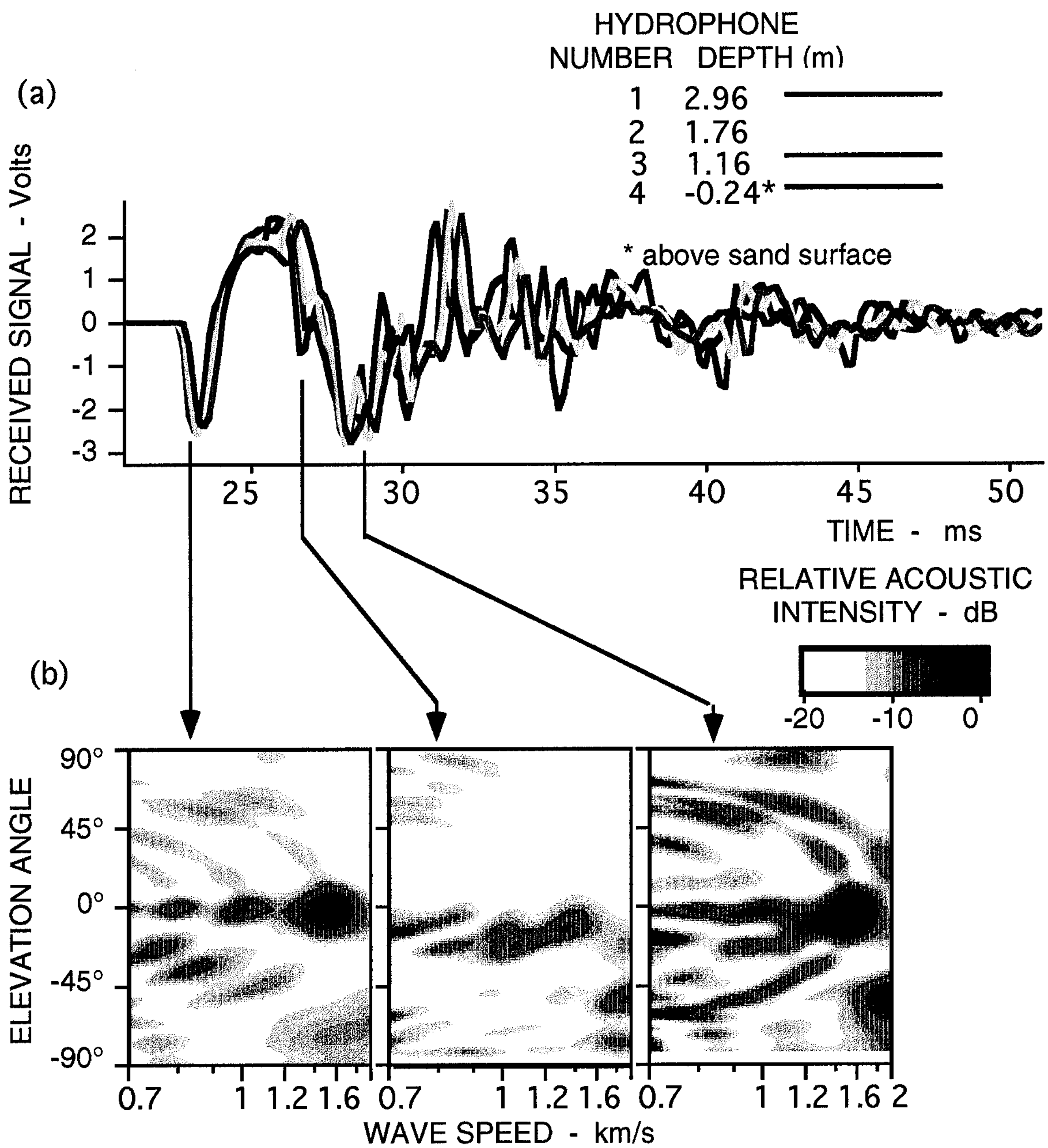

Figure 4.
Pings 54 to 57
(a) Signals received at hydrophones 1 - 4 at ping 54
(b) Direction and speed analysis results

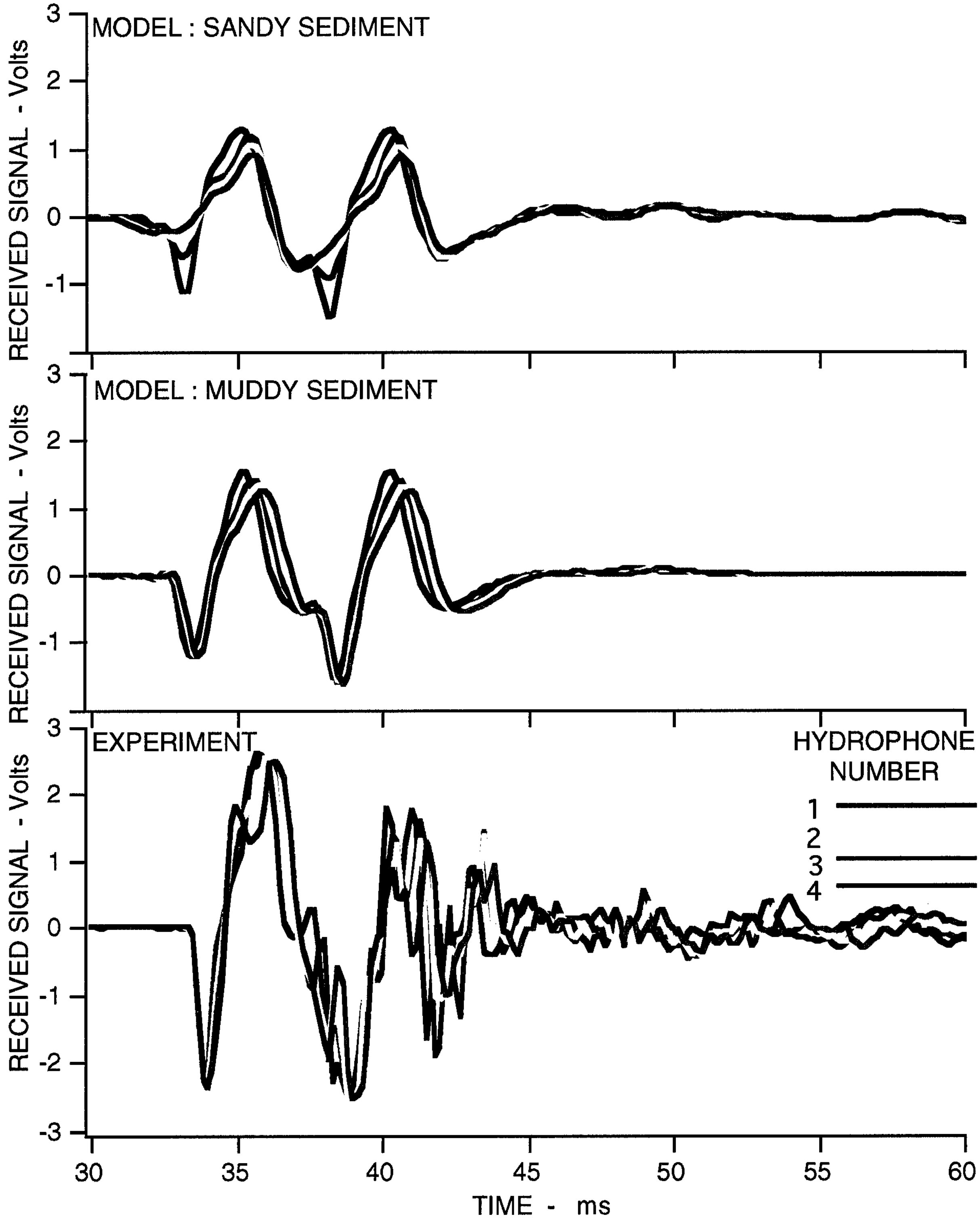

Figure 5.
Comparison between experiment and theoretical predictions of received pulse using sandy and muddy sediment models

$$V^{(1)} = \begin{bmatrix} -.0019i & 0 & 0 \\ .1795i & .0004i & 0 \\ .0009i & 0 & .0010i \end{bmatrix}$$

Columns represent monopole, dipole and quadrupole scattering amplitudes. Rows give rel-ative contributions from mismatches of compressibility, density and shear stiffness. Superscript "1" indicates a result of first-order perturbation.

Figure 6.
A sample scattering matrix ("vertex") from perturbation theory

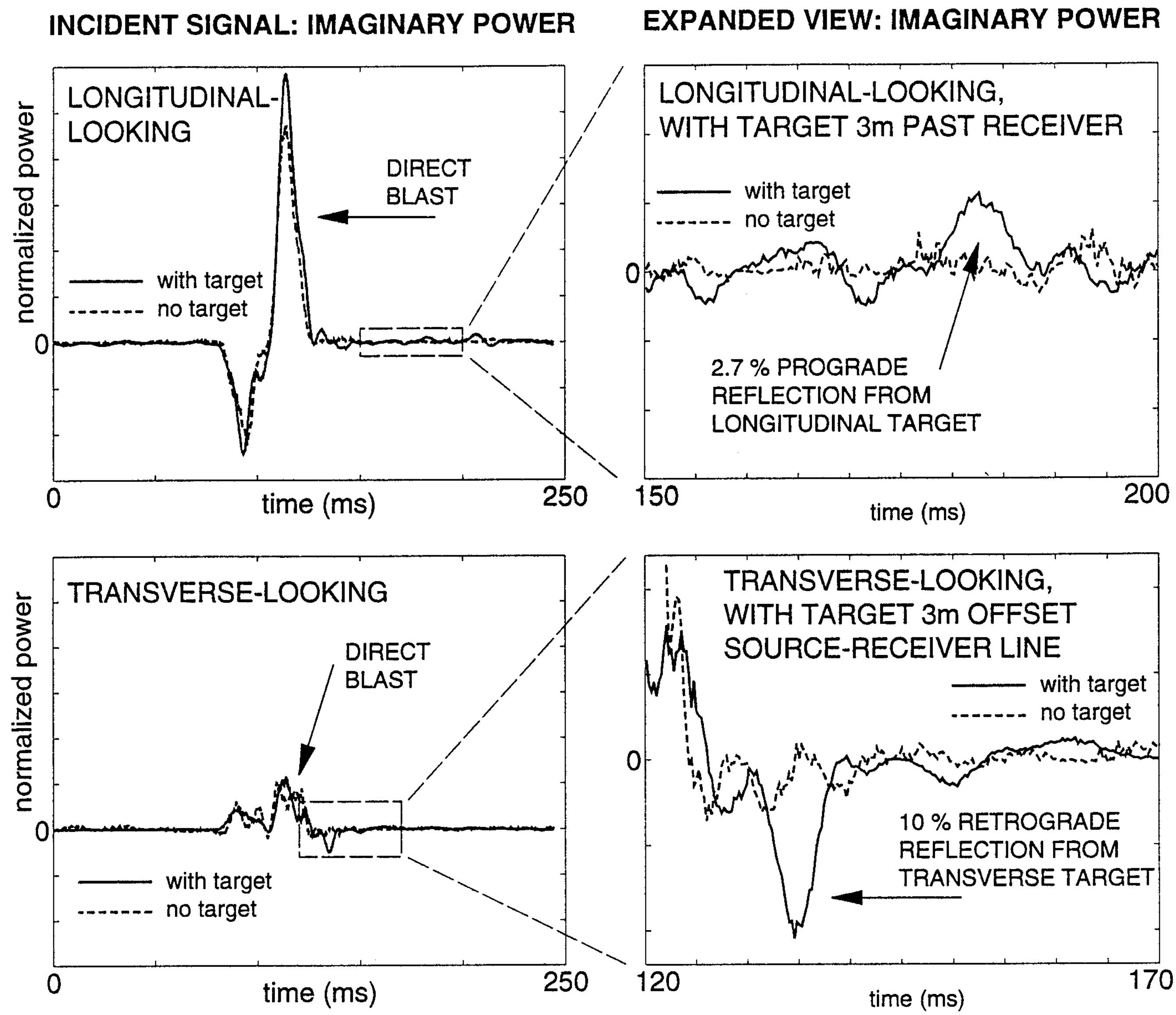

Figure 7.

Target reflections. Top: backscatter seen with receiver between source and target. Bottom: sidescatter seen with receiver transverse to source-target line.